N-64-2

NOLTR 63-96

THE NOL 10,000 ATM. BALLISTIC PISTON COMPRESSOR I. DESIGN AND CONSTRUCTION

11 JULY 1963

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 63-96

The work described in this report was carried out under Task FR-67, Spectroscopic Studies of High Pressure Gases. A new Ballistic Piston Compressor specifically designed for the study of the radiation emitted by extremely hot, dense gases is described. This new apparatus will make possible the experimental investigation of the effects of atomic collisions on spectral line widths, shapes, and positions over extended ranges of density and temperature.

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By direction

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INTRODUCTION

The study of the properties of extremely hot dense gases is not possible by static methods because of the limited strength of gas containers at elevated temperatures. Recently a rapid gas compression technique for studying optical properties of hot dense gases has been developed, by which a gas is compressed very rapidly to extremely high simultaneous values of pressure and temperature and then quickly brought back to normal pressure and temperature conditions (Ref. 1). The measurements of interest are made during the short period of time that the gas is in the hot dense gas state (Ref. 2, 3).

The apparatus described in Ref. 1 was that with which the rapid gas compression technique was developed, and with which the spectra described in Refs. 2 and 3 were produced. In the course of these experiments, however, a number of shortcomings of the compressor became evident. The principal limitations were (1) a short stroke resulting in a very small piston to end-plug separation at peak pressure, (2) 34 atm. reservoir design which limited maximum test gas pressures with monatomic gases to about 2,000 atm., (3) the high pressure section was integral with the tube resulting in limited flexibility in making modifications on the high pressure section, (4) inability to change pistons, windows, and pressure transducers without dumping all of the driver gas pressure from the reservoir, (5) non-uniform loading of the radiation viewing side window resulting in window failures at pressures in the vicinity of 2,000 atm., and (6) restriction to one fixed stroke-length of the compressor.

REQUIREMENTS

A value of 10,000 atm. maximum pressure of the test gas was chosen as the limit of the new apparatus. This requirement would affect the design of the high pressure section, the length of the tube, and the strength of the reservoir, as well as demand the use of pressure transducers and radiation viewing windows beyond the pressure range achieved with the old apparatus.

The new compressor should, in addition, incorporate modifications that would eliminate or reduce the shortcomings of the old compressor. The design requirements therefore consisted of the following:

Reservoir. The reservoir should be designed with a high enough working pressure to make possible the generation of the 10,000 atm. design pressure of the test gas. As monatomic gases require the highest driver gas pressure for a given test gas pressure, the reservoir should be designed for monatomic gases. In addition, it should be possible to seal off the opening in the reservoir that connects to the tube (Fig. 1), so that the apparatus can be worked on while the reservoir is fully loaded, thus making it unnecessary to dump all the gas from the reservoir each time an adjustment or change has to be made on the high pressure section or tube.

Stroke Length. The stroke of the piston should be sufficiently long so that for monatomic gases with an initial pressure of 1 atm. the minimum piston to end-plug separation at the maximum pressure of 10,000 atm. would not be less than 1 centimeter. With this relatively large piston to end-plug separation, the effects of the thin layer of relatively cool gas next to the walls would be minimized. In addition, a long stroke would allow the generation of the maximum design pressure with diatomic and triatomic gases without unduly small piston to end-plug separations. An additional desirable feature would be the ability to vary the stroke length of the compressor. This would make it possible to study the effects of optical depth on the observed emission.

High Pressure Section. The high temperatures and pressures generated by the rapid gas compression technique occur only after the piston has come within about 5 cm. of the end-plug. Consequently, only the very last part of the stroke requires the mechanical strength to contain a gas at 10,000 atm. pressure, as well as to withstand the accompanying momentary high values of surface temperatures. It follows, therefore, that the high pressure section should be separate from the tube, which can be of relatively low strength.

Radiation Viewing Window. The window should be located in the end of the high pressure section in such a manner that it is loaded symmetrically as the test gas is compressed. In addition, it should be positioned as close to the end of the compressor as possible, in order that the optical f-number is maximized.

Compression Rate. The rapid gas compression technique relies on a short time of compression to make the process essentially adiabatic, i.e., to reduce to a negligible amount the heat of compression that is lost by conduction to the walls and by mass leakage past the piston. This is accomplished by using a light, tight fitting piston. There is a limit, however, to the allowed compression rate above which shock waves are formed in the test gas. As the desired goal for which this compressor is designed is the production of a quantity of hot dense gas which is homogeneous throughout for ease of analysis of its emitted spectrum, it is clear that shock wave formation is to be avoided. The study of the radiation emitted by hot dense gases being traversed by shock waves might serve as an extension of the present optical studies with no modification to the compressor, aside from the use of a piston light enough to produce the desired strength shock waves.

Safety. The requirement that the high pressure section can be disassembled and the tube detached from the piston release section while the reservoir is fully charged with driver gas pressure makes it mandatory that the possibility of misfire of the compressor (accidental opening of the port which separates the driver gas from the piston before compressor firing) be eliminated. In addition, since the reservoir itself contains a large amount of high pressure gas, it should be designed with a large safety factor in order that it does not pose a safety hazard to personnel and to auxiliary equipment.

DESIGN

The compressor that was designed and constructed is shown in Fig. 1, and consists of four main parts, i.e., the reservoir, the piston release section, the tube, and the high pressure section. The compressor rests on five supports, the center three are steady rests, while the outer two consist of roller bearings. During assembly and alignment of the compressor all five supports are utilized. For firing, however, the three center supports are lowered and the compressor is then free to recoil on the two outer roller bearing supports without transmitting any force to the two tables. The two tables and the center support assembly are adjustable in height so that the compressor can be raised or lowered as necessary to align the radiation viewing window with the slit of the spectrograph. The piston release section is connected to the tube, and the tube to the high pressure section, with two coupling nuts. The threads on the piston release section and the high pressure section were made left-handed so that the compressor can be disassembled without any rotation of these three parts, i.e., unscrewing the two coupling nuts with the tube fixed results in axial motion of the piston release section (and reservoir) and high pressure section away from the tube.

Reservoir. The reservoir, shown in Fig. 2, was designed for a maximum operating pressure of 136 atmospheres and was tested to 200 atmospheres. The testing and certification was made by a separate concern from the one that fabricated the reservoir. With this reservoir it is possible to generate a 10,000 atm. test gas pressure with any gas with an initial test gas pressure of up to two atmospheres. The volume of the reservoir is about 60 liters, sufficiently large that the driver gas pressure does not drop more than about 15% as the piston travels down the tube.

Piston Release Section. The piston release section serves two functions: it fires the piston, and in addition makes possible the sealing-off of the reservoir gas from the tube in such a manner that the tube and high pressure section can be disassembled safely while the reservoir is fully charged with driver gas pressure. This feature greatly facilitates the experimental work, since it makes possible the exchange of pistons, windows, and pressure gages, and allows inspection of the tube bore and high pressure section, without time-consuming and expensive dumping of the reservoir pressure.

Figure 2 shows the piston release section in position between the tube and reservoir. It consists of a cylinder closed on one end with a cap to which is attached a piece of pipe. This pipe goes through the rear wall of the reservoir where a quick-opening solenoid-actuated valve is located. Four ports are located in the walls of the part of the cylinder which lies inside the reservoir. The two ends of a plunger located in the rear part of the cylinder bridge the four ports. The plunger necks down from a 7.61 cm. diameter on the reservoir side to a 4.44 cm. diameter on the tube side. The large-diameter part of the plunger contains two neoprene o-rings, while the small-diameter part contains one. In the forward position the plunger seals off the reservoir gas; subsequent motion to the rear position results in firing of the piston. A safety cap is screwed onto the tube end of the piston release section whenever the tube or high pressure section is disassembled while the reservoir is charged with driver gas pressure. An accidental loss of gas pressure behind the plunger, releasing the driver gas, would thus not endanger personnel or equipment.

Tube. The tube is 3.89 meters long and has a 50.09 mm. bore. The material is A.I.S.I. 4340 steel with a yield strength of 12,650 kg/cm^2 and a hardness of Rockwell C 42-45. It was fabricated from a discarded gas gun, hence the large outer diameter at the breech end and small outer diameter at the muzzle end. Actually, since the high pressures and temperatures are not generated until after the piston enters the high pressure section, the tube need not be designed for very high pressures. A simple calculation assuming a 12.1 cm. bore length in the high pressure section shows that with a monatomic gas initially at one atmosphere, the pressure as the piston enters the high pressure section is only 335 atmospheres and the temperature only 3,060°K. Diatomic and polyatomic gases have lower pressures and temperatures at this stage of the compression process.

The specifications for the straightness of the bore were that a brass plug 6 diameters long with O.D. 25 to 50 microns under the minimum bore diameter must pass through the entire tube. The tolerance for the 50 mm. bore diameter was ± 250 microns, but the diameter was not to vary by more than 25 microns once established. The ends of the tube bore and of the high pressure section bore were specified to be chamfered for a distance of 12.7 mm. to plus 0.254 mm. of the established diameter of the bore. The surface finish of the bore of the tube and of the high pressure section was specified to be 0.2 microns. The ends of the tube have o-rings for sealing the gas where the tube is coupled to the piston release and high pressure sections.

High Pressure Section. The body of the high pressure section (Fig. 3) is a thick-walled cylinder made of A.I.S.I. 4340 steel heat treated to a hardness of Rockwell C 42-45. The 50 mm. bore section is 17.78 cm. long; the wall thickness is 2.57 cm. A gas inlet is located in the wall for introducing the test gas into the compressor. This section was designed for pressures up to 5,000 atmospheres. An increase in wall thickness will be necessary for pressures between 5,000 and 10,000 atmospheres. Since the high temperatures which are generated in the high pressure section cause a slight vaporization of the inner walls with resulting emission of unwanted impurity radiation, three high pressure section bodies were constructed. Different platings on the bores of these high pressure sections will be tested in an effort to suppress the foreign emission and thus remove a complication to the analysis of the radiation. The bore of the first high pressure section has been fabricated with a 25 micron thick chromium plating. The surface finish of the plating was specified to be 0.2 microns.

Two window end-plug and two pressure gage end-plug assemblies were fabricated. The two window end-plugs are identical; one is shown installed in Fig. 3. The unsupported area has a diameter of 1.02 cm., through which the radiation passes. The end-plug surface adjacent to the window has a flatness of 1/10 to 1/2 fringe resulting in a gas seal that prevents the test gas from leaking out between the window mount and window.

There is also an o-ring located on the inside surface of the window cap which allows the tube to be pumped down, i.e., put under vacuum. This is necessary when the compressor tube is being flushed, or when the initial pressure of the test gas is to be lower than one atmosphere. In addition, an end-plug for a Kistler model 607 pressure gage, as well as for an N.O.L.-designed pressure gage, was made. The end-plugs are held in place by a closure nut (Fig. 3) and are positioned along the bore of the high pressure section by means of steel spacers. A Bridgman seal is located adjacent to the end-plugs to prevent leakage of the test gas. Two complete closure nut/end-plug assemblies were made, i.e., a window assembly, and a pressure gage assembly. In this manner it is possible to make identical alternate pressure measuring and radiation measuring shots by simply alternating the installation of two complete sub-assemblies.

Piston Positioning Rods. A positioning rod is used to position the piston at the desired station along the tube preparatory to a compressor shot. Normally a short positioning rod is employed as shown in Fig. 2. When this short rod is used, the maximum stroke of the compressor (3.89 meters) is utilized. In addition, however, an intermediate length and a long positioning rod were designed and fabricated. These two rods reduce the stroke of the compressor to one-half and to one-quarter of its maximum stroke. The use of different stroke lengths with the compressor should contribute to the determination of the optical depth of the test gas, as well as to make possible the study of the effect of piston velocity on shock wave formation.

Pistons. Six copper pistons were fabricated in the configuration of a right-circular cylinder (see Fig. 3). These were made in three different masses, i.e., 1 kg. (5.7 cm. long), 2 kg. (11.4 cm.) and 4 kg. (22.8 cm.). Two sets of these different mass pistons were made, one with an O.D. of 50.00 mm., and one of 50.04 mm. O.D. The first set gives a radial clearance of 45 microns with the compressor tube, the second set gives a 22 micron clearance. More sophisticated pistons containing gas seals for minimizing gas leakage past the piston during the piston motion, as well as modifications in configuration and use of other material, will be made as the need arises.

INSTRUMENTATION

Pressure Measurements. The pressure of the test gas during a shot is measured by a piezoelectric pressure transducer located in the end-plug at the same position as the window shown in Fig. 3. Three different pressure transducers are available for test gas pressure measurements: a Kistler 607 with a pressure range of 2,000 atm., a Kistler 605B/633B with a pressure range of 10,000 atm., and a NOL-designed pressure gage that is useful in the lower pressure range.

Bourdon pressure gages are used for adjusting the reservoir pressure and the plunger pressure. An aneroid gage is used for adjusting the test gas pressure preparatory to firing the compressor. The pressure of the driver gas during a shot is monitored by a strain gage pressure transducer located radially in the wall of the piston release section. In a similar manner, a transducer mounted axially in the cap at the back end of the piston release section monitors the gas pressure that actuates the plunger.

Piston and Plunger Position Indicator. The seating of the piston against the piston positioning rods closes a miniature switch located at the tip of the positioning rods. The closing of this switch turns on a light on the firing panel indicating that the piston is seated. When the short piston positioning rod is in place (Fig. 2), the slightly smaller bore diameter of the piston release section also acts as a stop, since the tip of the positioning rod is at the same axial position as the end of the piston release section bore. With the two longer rods positioning of the piston is accomplished solely by the piston positioning rods. The piston positioning rod circuit functions only when the plunger is in the firing position.

The forward and back position of the plunger is also indicated on the firing panel by indicator lights. In this case, the closing of a microswitch that is positioned in one of the ports of the piston release section by the rear part of the plunger (Fig. 2) indicates that the plunger is in the forward position. A second microswitch actuated by the front part of the plunger indicates that the plunger is in the back position.

Radiation Measurement. A Bausch and Lomb medium quartz prism spectrograph with a high-speed electromechanical shutter (Ref. 4) is used for recording the emission spectra. Two grating spectrographs, a 3 meter Baird, and a 1.5 meter Bausch and Lomb, are also available.

Control Circuits. Figure 4 is a schematic diagram of the compressor showing the gas lines and associated equipment that is used for operating the compressor.

OPERATION

The compressor is assembled as shown in Fig. 1. The plunger is seated, i.e., moved into position to seal the opening between the reservoir and the tube, by increasing the pressure of the gas behind the plunger. With the plunger seated, the o-ring located at the forward end of the plunger forms a seal between the reservoir and the tube. The reservoir is then flushed with the driver gas and adjusted to the desired firing pressure.

If the emitter (i.e. atom whose spectrum is to be investigated) is to be added in powder form, it is introduced into the high pressure section by disengaging the coupling nut that connects the high pressure section to the tube. The piston is seated by slightly increasing the gas pressure ahead of the piston and the tube is then flushed with the test gas. Finally the pressure of the test gas, i.e., the gas in the tube ahead of the piston, is adjusted to the desired initial pressure and the compressor is ready to be fired. Firing is accomplished by reducing the pressure behind the plunger to a value sufficiently below the reservoir pressure that the plunger is forced to the extreme rear of the piston release section. This dumping of the pressure behind the plunger is accomplished by opening a solenoid-actuated quick-opening valve located in the gas line connected to the rear of the piston release section. When this happens, the high pressure driver gas in the reservoir rushes through the 4 ports in the piston release section, and propels the piston down the tube. As the piston travels down the tube the test gas trapped ahead of it is rapidly compressed to some maximum pressure and temperature principally determined by the initial test gas pressure, the reservoir pressure, and the adiabatic exponent of the test gas. Since the piston is free, it oscillates back and forth in the tube a number of times before it comes to rest due to the force of friction along the tube walls. The compressor recoils freely on its ball-bearing supports without transmitting any horizontal force to the two end tables. A small amount of driver gas leaks across the piston during that portion of its flight down the tube where the driver gas pressure is higher than the test gas pressure. To prevent this gas leakage from contaminating the test gas, the same gas is used for driving the piston as that being compressed. If the next shot is to be made without disassembly of any part of the compressor, the flushing of the tube can be dispensed with. If the high pressure section is to be disassembled before the next shot, the tube must then be flushed, otherwise the procedure for making successive shots is identical with that described above.

IDEAL GAS CALCULATIONS

The values of temperature and relative density (relative to that at NTP) that can be generated in an ideal monatomic gas by adiabatic compression have been calculated up to the 10,000 atm. pressure design limit of the ballistic piston compressor, and are given in Fig. 5. These calculations were made for an initial test gas temperature of 298°K, and initial test gas pressures ranging from 2 atm. down to 0.1 atm. Although the compression process in the ballistic piston compressor is not completely adiabatic due to heat transfer to the walls of the high pressure section and gas leakage of the test gas past the piston, the rapidity of the gas compression (i.e., approximately 1 millisecond) results in a process that is very nearly adiabatic. The curves of Fig. 5, therefore, should be good approximations to the conditions generated in the compressor. The accompanying piston/end-plug separations and reservoir pressures were calculated and are given in Fig. 6.

ACKNOWLEDGEMENT

The author wishes to express his gratitude to Mr. George Peet for the idea that finally evolved into the design of the piston release section, and to thank Mr. Rolf Goderstad for his able assistance in the design of the high pressure section. The many contributions of Messrs. Gordon Hammond, Paul Kendall, Fred Sheckels, and Jesse Hawkins are also gratefully acknowledged.

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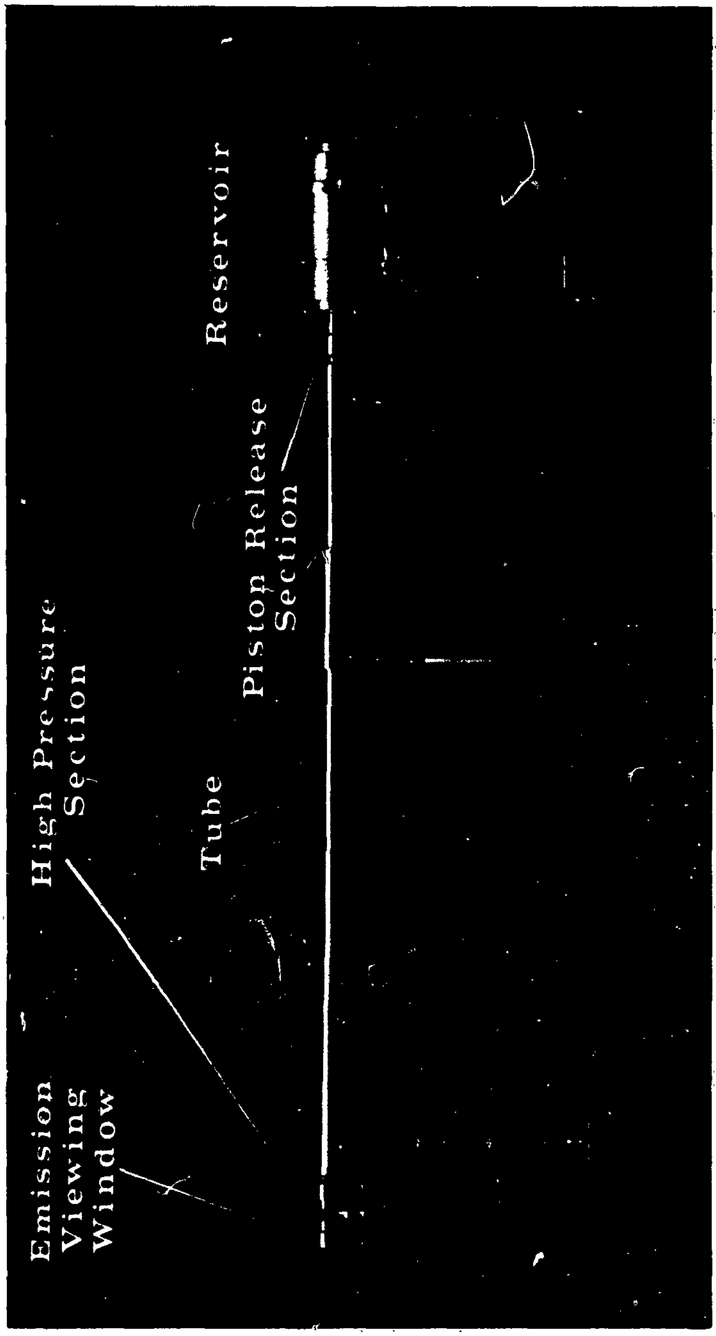

FIG. I BALLISTIC PISTON COMPRESSOR

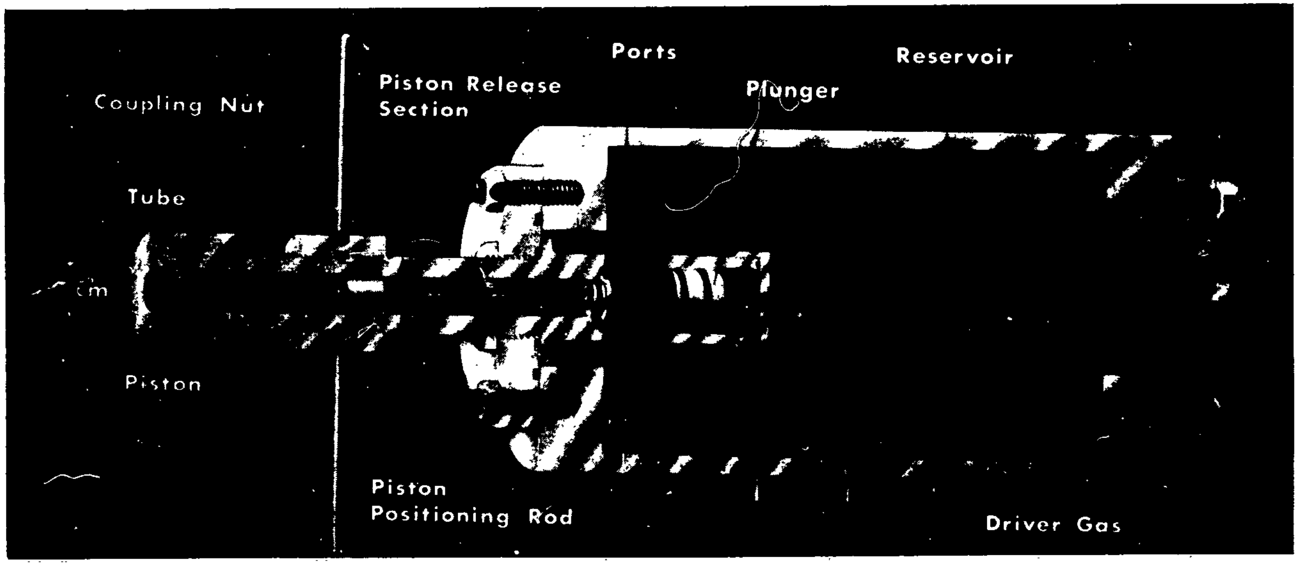

FIG. 2 BALLISTIC PISTON COMPRESSOR (RESERVOIR END)

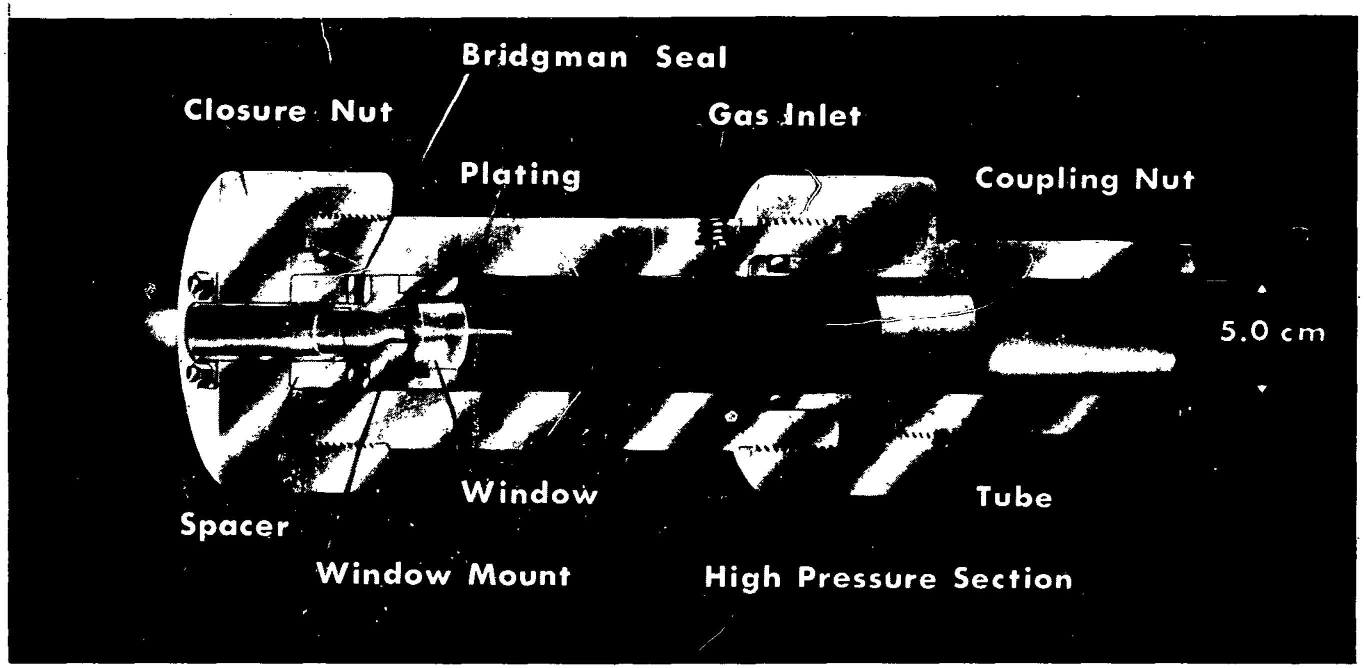

FIG. 3 BALLISTIC PISTON COMPRESSOR (HIGH PRESSURE END)

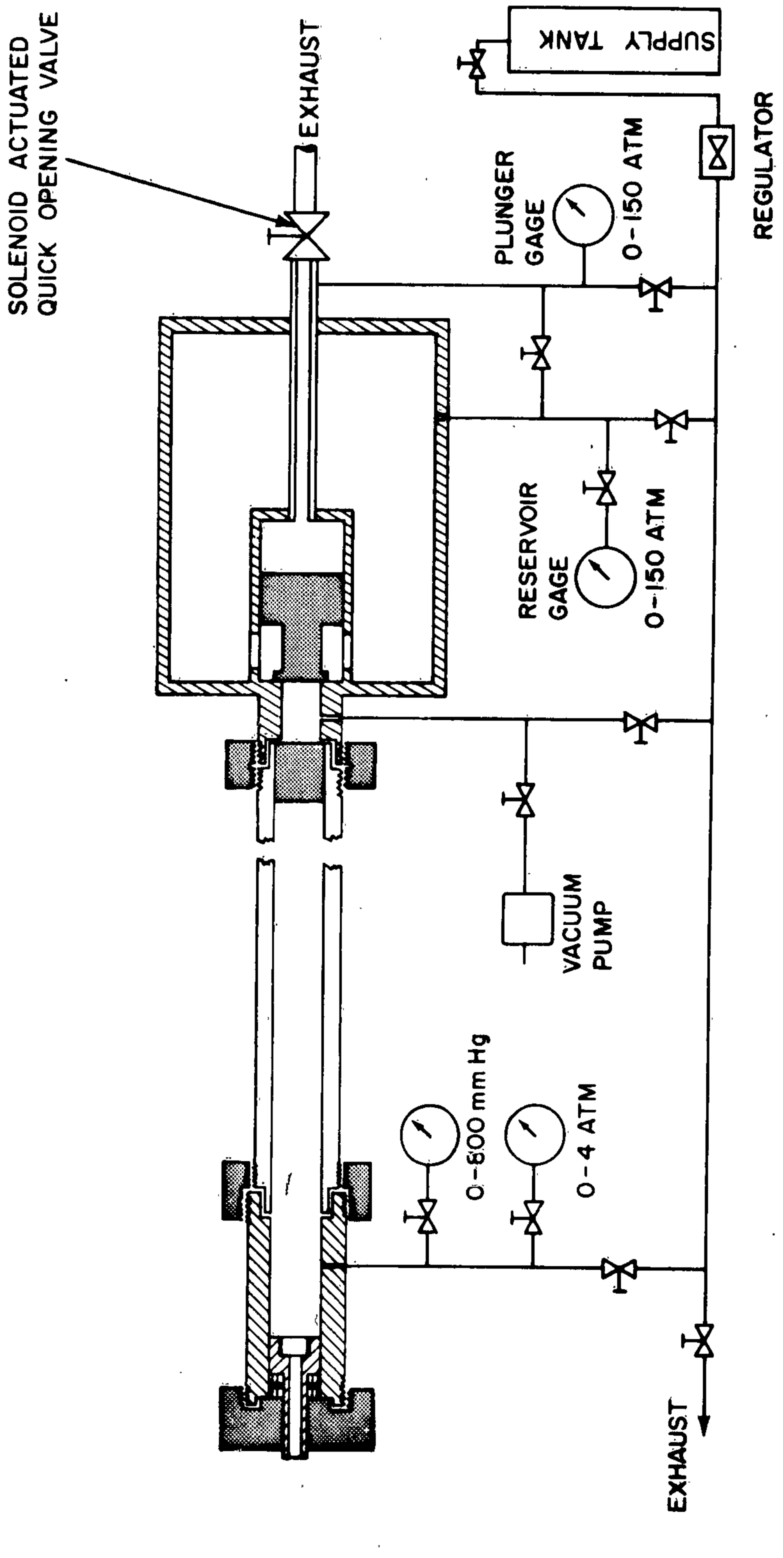

FIG. 4 GAS LINE SCHEMATIC DIAGRAM

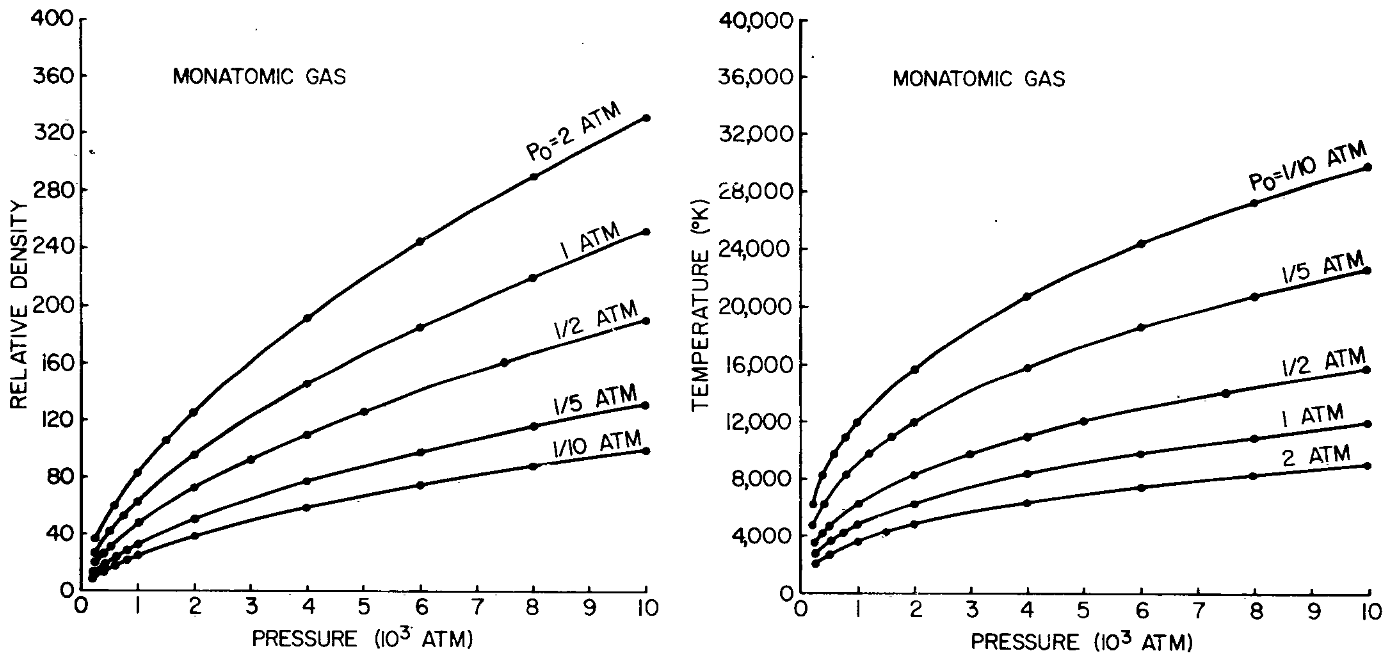

FIG. 5 RELATIVE DENSITY AND TEMPERATURE VERSUS PRESSURE OF AN IDEAL MONATOMIC GAS ADIABATICALLY COMPRESSED FROM FROM AN INITIAL TEMPERATURE OF 298°K

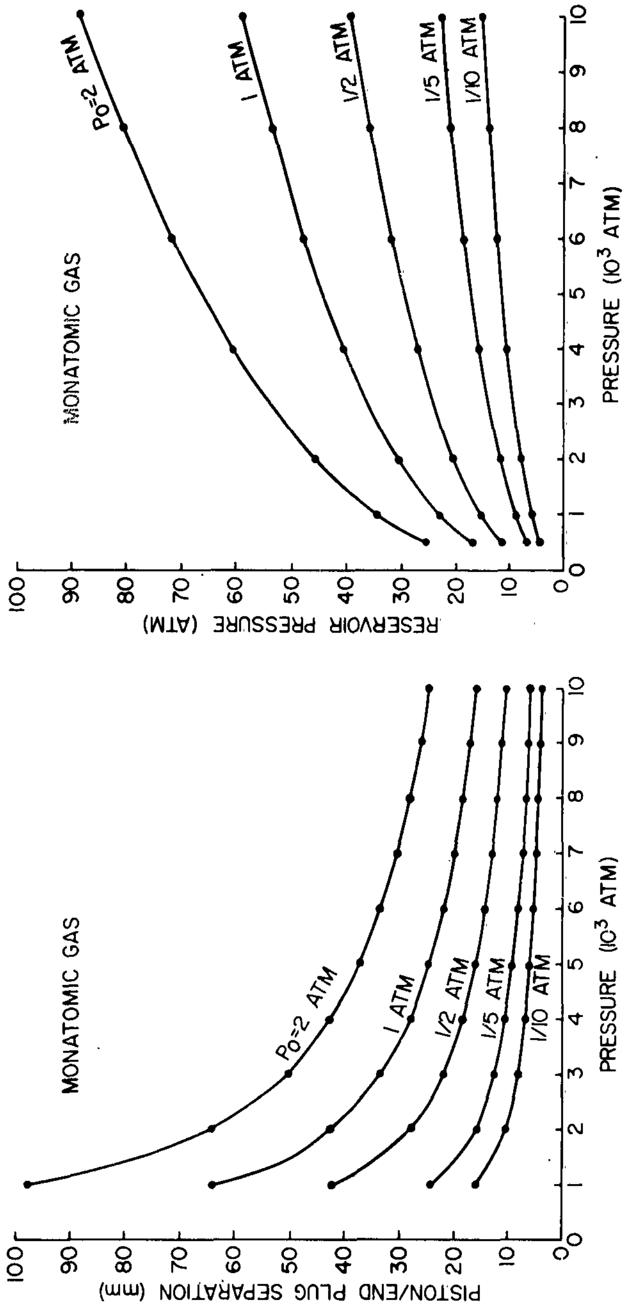

FIG. 6 PISTON/END PLUG SEPARATION AND RESERVOIR PRESSURE VERSUS PRESSURE OF AN ADIABATICALLY COMPRESSED IDEAL MONATOMIC GAS

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SOURCE	NOL technical report	NOLTR	SECURITY CLASSIFICATION AND CODE COUNT	Unclassified - 26	UØ26
REPORT NUMBER	63-96	63ØØ96	CIRCULATION LIMITATION		
REPORT DATE	11 July 1963	Ø763	CIRCULATION LIMITATION OR BIBLIOGRAPHIC		
			BIBLIOGRAPHIC (SUPPL., VOL., ETC.)		

SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Ballistic	BALR	Gases	GASE	Tube	TUBE
Piston	PISN	Radiation	RADT	Instrumentation	INSM
Compressor (design)	CMPSD	Test facilities	TESF		
Compressor (construction)	CMPSF	Equipment	EQUI		
Compressor	CMPS	High temperature	HTEM		
10,000	1ØØØØ	Temperature	TEMP		
Atmospheric	ATMO	Calculations	COMA		
Pressure	PRES	Density	DENS		
Rapid	FAST	Volume	VOLU		
Compression	COMR	Hot	HOTZ		
High pressure	HIGP	Reservoir	REER		
Pressure	PRES	Requirements	REQI		

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 63-96)
THE N. O. L. 10,000 ATM. BALLISTIC PISTON COMPRESSOR. I. DESIGN AND CONSTRUCTION, by George T. Lalos. 11 July 1963. 10p. illus. NOL task FR-67. UNCLASSIFIED

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1. Gases - Radiation
2. Gases - Compressibility
3. Gases - High Pressure
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II. Lalos, George T.
III. Project

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